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Erodibility of a soil drainage sequence in the loess uplands of Mississippi

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ABSTRACT

The susceptibility of loess soils in the lower Mississippi to runoff and erosion losses varies as a function of landscape position and mapping units. This study was conducted to determine the effects of soil drainage on physical and chemical properties that influence erodibility through their control of aggregate stability. Soil samples were collected from the A- and B-horizons of the five representative pedons in the Memphis catena whose drainage class varied from well-drained to poorly-drained. The fine earth fraction (<2 mm) of each soil was characterized for a range of basic soil physical and chemical properties. Additional sub-samples (<8 mm) were placed in a rainfall simulator pan (0.6 m×0.6 m test area) and subjected to simulated rainfall at an intensity of 64 mm h^{-1}. Soil erodibility was assessed by the use of an aggregation index (AI) computed from water dispersible clay (WDC) relative to total clay contents. The data show that as soil drainage classes became wetter, the percentage of sediment <53 µm increased with a decrease in soil AI resulting from a loss of Fe, Al, and Si oxide cementing agents. These results suggest that cementing agents responsible for soil aggregate stabilization are mobilized under conditions of relatively low redox potentials which increase soil erodibility.

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1. Introduction

Water erosion losses within a soil mapping unit are determined by rainfall characteristics, topography, and surface cover. Differences in erosion losses between soil mapping units can be attributed to differences in soil properties that determine soil erodibility. Soil erodibility is defined as the inherent susceptibility of a soil to erosion forces represented by raindrop impact, overland flow, and throughflow (Bryan, 1968; McIntosh and Laffan, 2005). Since erodibility is a fundamental soil characteristic, its magnitude is determined by other soil properties such as texture, structure, aggregate stability, and shear strength (Le Bissonnais et al., 2006). In conjunction with erodibility, slope is critical to determining the degree to which individual soil mapping units erode, since erosion losses generally increase in response to an increase in erodibility or slope (McIntosh and Laffan, 2005). Aggregate stability is a critical component of soil erodibility since it controls soil dispersion, surface seal development, and thus the extent to which runoff occurs. The primary soil components responsible for aggregate stabilization are the cementing agents of Fe and Al oxides, and organic C that bind individual soil particles into stable structural units. Thus, aggregate stability is essentially a measure of the tendency of cemented clay particles to disperse in water, as indicated by water dispersible clay contents, a measure of soil erodibility. Aggregate stability and soil erodibility are inversely related.

The distribution of soil erodibility in the landscape is closely related to slope factors (aspect, gradient, position) through their control of soil water distribution and ultimately soil properties that control aggregate stability. More specifically, in a study of slope aspect and position, Franzmeier et al. (1969) measured higher concentrations of organic C on north-facing slopes which normally have cooler soil temperatures and higher soil water contents. Relative to slope position, other scientists (Honeycutt et al., 1990; Pierson and Mulla, 1990; Rhoton et al., 2006) recorded greater organic C concentrations and aggregate stability on footslope and toeslope positions. Particle size distributions and the concentration of divalent cations strongly influence the variability of aggregate stability between slope positions. Young and Hammer (2000) reported higher silt contents and lower basic cation concentrations on backslope positions relative to higher slope positions. Franzmeier et al. (1969) also found coarser particle size distributions on backslope positions, and the highest basic cation concentrations on the footslope positions. These differences in soil properties were found to account for 40% of the variability in erodibility on a Canadian Prairie landscape (Martz, 1992). In terms of individual slope positions, the highest erodibility was associated with the shoulder and backslope positions. Relative to these two positions, erodibility was 14% lower on the summit and footslope positions, and 21% lower on the toeslope position. Considerably less work has been conducted on erodibility as a function of slope gradient, however, soil property trends between the different

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slope classes appear to be a critical deciding factor. Using aggregation index as an indicator of erodibility, Rhoton et al. (2007) recorded the lowest soil erodibility on E (13–20%) and F (>20%) slope classes relative to slopes of a lower gradient in a semiarid watershed. The soils formed on the steeper slopes had higher clay and nutrient contents which contributed to greater soil organic C contents and aggregate stability.

Landscape position, through its control of soil hydrology, strongly affects soil properties and behavior by influencing weathering, soil development, friability, and permeability, and thus erosion in some cases (Herbel and Gile, 1973). Soils that are saturated on a seasonal basis develop hydromorphological features including redoximorphic concentrations and depletions created by Fe and Mn movement, and an accumulation of organic matter in the surface of the wetter soils (Galusky et al., 1998). Morphologically, soil color is the most obvious response to changes in soil hydrology between landscape positions. The ability to relate soil color to water tables and drainage conditions (Lindbo et al., 1998) led to the development and application of the soil drainage class concept (Galusky et al., 1998). Relative to soil drainage class effects on soil aggregation and erodibility, Fe oxide contents between slope positions are all important since this soil property is redox dependent. Goldberg (1989) indicated that Fe oxides are influential in the stabilization of soil aggregates if soil pH is below their zero point of charge. Conversely, Borggaard (1983) suggested that Fe oxides are not important to soil aggregation. These two findings indicate that the importance of Fe oxides to soil aggregation may vary with differences in mineralogy/crystallinity between soils and/or slope positions. Rhoton et al. (1998), in a study of Fe oxide crystallinity-soil aggregation interactions found that soils formed on the lower, wetter slope positions were less erodible than the soils on the upslope positions. The differences in erodibility were attributed to a relative abundance of ferrihydrite in the wetter slope positions. Ferrihydrite is poorly crystalline Fe oxide mineral that is much more reactive than the more crystalline, goethite and hematite species that predominate in the better drained parts of the landscape. Similar findings have been reported with respect to the distribution of other poorly crystalline Fe oxide minerals in soil hydrosequences (Smeck et al., 2002).

The loess uplands of Mississippi consist of approximately 2.5 million hectares formed from glacial outwash sediments that were deposited in the floodplain of the lower Mississippi River Valley, and eventually blown east and re-deposited between 9000 and 20,000 yr ago (Pye and Johnson, 1988). Loess thickness ranges from 4.6 to 21.3 m at the Mississippi River bluff to 0 within 161 km to the east (Wascher et al., 1947). The intensively farmed, highly erodible soils of the Memphis catena (Memphis, Loring, Grenada, Calloway, Henry) dominate these loess deposits. Estimated soil erosion losses for the region, which range from 34 to 56 Mg ha^{-1} yr^{-1} (Langdale et al., 1985), are generally considered the highest in the United States. These high erosion losses have so severely degraded soil productivity that vast areas have gone out of production, and simultaneously created some of the worst impaired stream systems in the country.

Erosion research conducted on some of the soils in this hydrosequence (Meyer and Harmon, 1984) has shown that the well-drained Memphis soil is more erodible than the moderately well-drained Grenada. Further, the Memphis soil has been shown to yield more fine sediment than Grenada, suggesting that erodibility varies as a function of drainage class (Meyer et al., 1980; Rhoton et al., 1982). Soil characterization as a function of landscape position is critical to erosion and sedimentation studies at the watershed scale especially when soil mapping units differ substantially in terms of properties that control erodibility and hydrology. Likewise, the spatial variability of these soil properties within a given mapping unit should be expressed at the watershed scale. In this regard, particular attention should be placed on soil erodibility relationships to slope position and soil wetness since this factor has such a strong influence on the formation and distribution of clays, Fe and Al oxides, and organic C. Zones formed by differences in soil wetness and erodibility can be mapped and used to predict sediment and chemical losses from watersheds. Thus, the objectives of this research were to determine how soil properties that affect erodibility vary between slope position and drainage class for a hydrosequence of soils developed in loess deposits of the lower Mississippi River Valley.

2. Materials and methods

2.1. Sample collection and characterization

The soil samples used in this study were collected near Senatobia, MS (34° 31′ Lat. N, 89°57′ Long. W) from the A and B horizons of representative pedons in the Memphis catena. The component soils are: Memphis (fine-silty, mixed, active, thermic Typic Hapludalfs), Loring (fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs), Grenada (fine-silty, mixed, active, thermic Oxyaquic Fraglossudalfs), Calloway (fine-silty, mixed, thermic Aquic Fraglossudalfs), and Henry (coarse-silty, mixed, active, thermic Typic Fragiaqualfs). Relative to drainage class, the Memphis is well-drained, Loring and Grenada are moderately well-drained, Calloway is somewhat poorly drained, and Henry is poorly drained. The definitions of the various drainage classes are those established by the Soil Survey Staff (1993). Land-use in all cases was pasture.

In the laboratory, the soils used for chemical and physical analyses were air-dried, crushed, and sieved to <2 mm. Particle size analysis used the pipette method of Day (1965) and samples that had been dispersed by shaking overnight in Na-hexametaphosphate. The water dispersible clay (WDC) contents of the soils were determined by the same pipette method following overnight dispersion in distilled water. An aggregation index (AI) was calculated for each soil according to the method of Harris (1971) as follows: $AI = 100\,(1 - WDC/\text{total clay})$. Soil aggregate stability is directly proportional to the AI value of a soil. Soil colors were measured quantitatively using a Minolta CR-200 Chroma Meter (Minolta Corp., Ramsey, NJ). The redness ratio (RR) was calculated as follows: $RR = (10 - H)\,C/V$, where H is the numerical value of YR hue, C is chroma, and V is value using Munsell notation (Torrent and Barrón, 1993). Magnetic susceptibility was determined with a Bartington MS-2 Magnetic Susceptibility Meter (Bartington Instruments LTD., Oxford, England). Organic C samples were combusted in a Leco CN-2000 Carbon Analyzer (Leco Corp., St. Joseph, MI). Soil pH was determined in a 1:1 soil/distilled water suspension (McLean, 1982). Sodium citrate–bicarbonate–dithionite (CBD) and acid ammonium oxalate (AAO) extractable Fe, Al, and Si contents were determined by the methods of Mehra and Jackson (1960), and Schwertmann (1964), respectively. Iron and Al concentrations in the extracts were measured with Perkin-Elmer 2380 atomic absorption spectrophotometer. Extractable Si was determined by colorimetric methods (Hallmark et al., 1982). Exchangeable cations were extracted with 1 M ammonium acetate at pH 7.0 (Thomas, 1982) and analyzed by atomic absorption spectrophotometry. Cation exchange capacity was determined by the 1 N sodium acetate method (National Soil Survey Center, 1996).

2.2. Erodibility determinations

The erodibility portion of the study was conducted in the laboratory using a rainfall simulator pan designed by Bradford and Huang (1993) which had a test area of 0.36 m^2 (0.6 m by 0.6 m) surrounded by a 0.3 m wide border to minimize splash losses. Total depth of the pan was 15.2 cm, with a 7.6 cm thick sand bed in the bottom covered with a porous nylon cloth to prevent soil movement into the sand. The surface 7.6 cm were filled with soil samples that had been sieved to <8.0 mm. Once the soil surface was leveled and the slope of the pan had been adjusted to 5%, simulated rainfall was applied to two replications of the air-dry soils at an intensity of 6.4 cm h^{-1} for 1 h using a variable intensity rainfall simulator (Meyer and Harmon, 1979). Untreated well-water having an electrical conductivity of 4.89×10^5 S m^{-1} was used as the water source.

Table 1
Selected physical properties of Memphis catena soils used in the study

Soil/horizon	Particle size distribution					Munsell color			Redness rating	Magnetic susceptibility
	Sand	Silt	Clay	WDC	AI	Hue	Value	Chroma		
	g kg^{-1}									10^{-8} m^3 kg^{-1}
Memphis A	35	824	141	53	62	8.1 YR	3.1	2.4	1.47	58.5
Memphis B	11	688	301	103	66	7.7 YR	3.3	3.7	2.60	66.9
Loring A	26	824	150	49	67	8.3 YR	3.3	2.8	1.44	63.4
Loring B	10	707	283	100	65	7.6 YR	3.4	3.8	2.68	66.8
Grenada A	31	803	167	62	63	8.6 YR	3.2	3.2	1.40	50.0
Grenada B	10	717	273	88	68	8.1 YR	3.4	4.1	2.29	41.1
Calloway A	59	847	94	44	53	8.8 YR	3.2	2.5	0.94	43.3
Calloway B	24	768	208	92	56	8.8 YR	3.4	3.5	1.24	39.1
Henry A	56	750	194	97	50	8.6 YR	3.4	1.9	0.78	10.9
Henry B	46	823	131	72	45	9.3 YR	4.1	1.8	0.31	6.0

Runoff samples were collected for determination of sediment size distributions at intervals of 17 to 20, 37 to 40, and 57 to 60 min into the rainfall simulator run. Once collected, the sediment was immediately separated into its >2000, 2000 to 1000, 1000 to 500, 500 to 250, 250 to 125, 125 to 53, 53 to 20, 20 to 5, 5 to 2, and <2 µm fractions, following standard wet sieve and pipette procedures, oven-dried at 70 °C, and weighed. A weighted sediment sample was collected from this residue, and shaken overnight in Na hexametaphosphate to determine the dispersed particle size distribution for comparison with the undispersed sediment. The bulk sediment collected at 0 to 17, 20 to 37, and 40 to 57 min into the runs was fractionated to >250 µm, 250 to 53 µm, and <53 µm by wet sieving, then oven-dried at 70 °C, and weighed. The physical and chemical properties of the sediment were determined from these fractions using procedures identical to those of the soils. All statistical analyses used the GLM Procedure of SAS version 8 (SAS Institute, 1999).

3. Results and discussion

3.1. Soil properties

The physical and chemical characteristics of the various soils are shown in Tables 1 and 2, respectively. The particle size data (Table 1) are consistent with those for relatively uneroded loess-derived soils in upland areas of the lower Mississippi River Valley. The B-horizons contain substantially greater concentrations of clay, as expected, with the exception of the Henry soil where the clay content of the A-horizon is greater. This is probably the result of run-on from upslope since the Henry soil occurs in depressions on toeslope positions. Soil textures were primarily silt loam in the A-horizons, and silty clay loam in the B-horizons. On the basis of WDC contents in the A-horizons, the Calloway and Loring soils have the most stable aggregates, and the Henry is the least stable. When the total clay content is used with WDC to calculate an AI, both the A- and B-horizons in the more poorly drained soils (Calloway, Henry) are substantially less stable than the other better drained soils. The soil colors are also indicative of differences in drainage class. Specifically, the yellow red (YR) hues become progressively more yellow going from the well-drained to poorly drained conditions. The color components did not show much variation with the exception of chroma in the Henry soil. This suggests that the Fe oxide coloring agents in these soils have been mobilized under conditions of low redox potential. This is substantiated by the redness ratings (RR) which are at a maximum in the well-drained and moderately well-drained soils (Memphis, Loring, Grenada). By contrast, the poorly drained Calloway and Henry soils have a much lower RR. With the exception of the Henry, the RR of the B-horizons were considerably greater than their respective A-horizons reflecting the greater contents of translocated clay and Fe oxides (discussion to follow). Magnetic susceptibility is also strongly related to drainage class. The highest readings were recorded for the well-drained (Memphis) and moderately well-drained (Loring) soils. Magnetic susceptibility decreased steadily downslope from the Loring, which had readings of 63.4 and 66.8×10^{-8} m^3 kg^{-1} in the A- and B-horizons, to lows of 10.9 and 6×10^{-8} m^3 kg^{-1} in the Henry A- and B-horizons. Similar relationships have been reported elsewhere between slope positions and magnetic susceptibility (Alekseyev et al., 1989; de Jong et al., 2000). Apparently, as the soils become wetter the magnetic mineral component (magnetite) is progressively depleted through redox reactions leading to a lower susceptibility.

The extractable cation concentrations for the five soils do not show much variation other than low Ca contents in the Henry (Table 2). Similar results were recorded for the CEC values, with the Henry B-horizon having basically no exchange capacity. Soil pH was relatively uniform between soils since fertility levels and liming had not been maintained. The primary differences in organic C (OC) contents occurred between the Henry and other soils. Specifically, OC concentrations in the Henry were substantially greater, suggesting OC is accumulating in this soil due to its lower position on the

Table 2
Selected chemical properties of Memphis catena soils used in the study

Soil/horizon							Organic	Dithionite extractable			Oxalate extractable			
	Ca	Mg	K	Na	CEC	pH	C	Fe	Al	Si	Fe	Al	Si	Fe_o/Fe_d
	cmol$^+$ kg^{-1}						g kg^{-1}	g kg^{-1}						
Memphis A	4.6	2.2	0.4	0.1	16.7	4.9	23.9	9.9	1.5	0.80	4.2	1.4	0.25	0.42
Memphis B	7.3	3.0	0.4	0.1	20.3	5.1	4.8	16.9	2.4	1.00	6.8	2.5	0.52	0.40
Loring A	4.0	2.0	0.3	0.1	13.6	4.8	18.0	9.3	1.5	0.80	3.8	1.4	0.30	0.41
Loring B	4.0	3.0	0.3	0.2	17.5	4.8	3.8	16.4	2.3	1.00	6.5	2.4	0.52	0.40
Grenada A	4.6	1.8	0.2	0.2	14.5	5.0	16.0	12.9	2.0	0.70	4.5	1.6	0.30	0.35
Grenada B	3.3	2.2	0.2	0.1	18.7	4.9	4.5	19.6	3.2	1.20	4.9	2.3	0.45	0.25
Calloway A	4.4	1.3	0.3	0.1	14.3	5.1	19.4	9.2	1.4	0.60	5.2	1.4	0.34	0.57
Calloway B	6.8	1.8	0.1	0.1	14.9	5.5	4.4	12.7	2.0	0.60	5.4	1.7	0.35	0.43
Henry A	1.6	0.3	0.1	0.1	14.9	4.6	34.0	7.7	2.3	0.60	6.0	2.3	0.24	0.78
Henry B	0.5	<0.1	0.3	0.1	0.4	4.7	10.4	3.2	1.3	0.40	0.9	1.3	0.15	0.28

Table 3
Ratio of undispersed to dispersed sediment size distributions

Soil/horizon	Sand			Silt			Clay		
	Undispersed	Dispersed	Ratio	Undispersed	Dispersed	Ratio	Undispersed	Dispersed	Ratio
	g kg^{-1}			g kg^{-1}			g kg^{-1}		
Memphis A	647	38	17	273	807	0.34	80	155	0.52
Memphis B	579	9	64	353	666	0.53	68	325	0.21
Loring A	539	23	23	435	817	0.53	26	160	0.16
Loring B	585	10	59	369	687	0.54	46	303	0.15
Grenada A	632	25	25	338	776	0.44	30	199	0.15
Grenada B	577	12	48	333	685	0.49	90	303	0.30
Calloway A	657	72	9	301	827	0.36	42	101	0.42
Calloway B	485	29	17	473	749	0.63	42	222	0.19
Henry A	689	41	17	229	785	0.29	82	174	0.47
Henry B	300	28	11	622	851	0.73	78	121	0.64

landscape where poorly drained conditions slow oxidation rates. The differences between Memphis and the other soils may be a function of increased runoff on the Loring and Grenada soils which occur on the steeper portions of the landscape. The slightly higher OC contents in the Calloway soil may reflect upslope OC contributions as run-on. This enrichment of OC in runoff is consistent with the results reported on a watershed scale (Rhoton et al., 2006).

The Fe_d shows the most variability between soils and drainage classes relative to the CBD extractable components (Fe_d, Al_d, Si_d). With the exception of Henry, the greatest concentrations were recorded in the B-horizons in conjunction with clay contents. As expected, the greatest differences occur in the poorly drained soils where the more strongly reducing conditions have resulted in the conversion of crystalline Fe oxides to more amorphous and/or elemental forms. The Al_d does not show any apparent trends between drainage classes. Again, the higher concentrations occur in the B-horizons except for the Henry soil. The Si_d concentrations decrease substantially as the drainage classes become progressively wetter, especially in the B-horizons of the poorly drained members. Apparently, this element is subject to mobilization under strongly reducing conditions similar to Fe and Al, which has resulted in large decreases in the AI for these soils. Relative to the AAO extractions (Fe_o, Al_o, Si_o) Fe_o concentrations were generally two to three times lesser than the CBD data regardless of horizon, with the least B-horizon values recorded for the poorly drained soils. The Al_o contents were very similar to Al_d with basically no variation between soils except for low values for the Calloway and Henry B-horizons. These two soils also contained the lowest Si_o concentrations in the B-horizons which were two to three times lower than the CBD component. The Fe_o/Fe_d ratios for the better drained Memphis, Loring, and Grenada soils were lower than those of the more poorly drained soils with the exception of the Henry B-horizon. This is an indication that under more poorly drained conditions, a greater amount of Fe_d is converted to Fe_o. Generally, the greater Fe_o/Fe_d ratios are associated with lower levels of soil erodibility (Rhoton et al., 1998).

3.2. Sediment characteristics

The undispersed and dispersed sand, silt, and clay fractions of the sediment appear as the mean of two replications in Table 3. All of the A-horizons soils eroded predominantly as sand-sized (>53 µm) aggregates. These concentrations ranged from 539 (Loring) to 689 g kg^{-1} (Henry). However, based on the undispersed to dispersed ratio, the Grenada A (25) was the best aggregated, followed by Loring (23), Memphis and Henry (17), and Calloway (9). In the silt-sized category (53 to 2 µm), the Loring A had the greatest amount of aggregated sediment with a ratio 0.53, and the Henry had the least at 0.29. The Grenada (0.44) was slightly lower than Loring followed by Calloway (0.36) and Memphis (0.34). The greatest amounts of sediment eroding as clay sized (<2 µm) came from the Memphis (0.52), Henry (0.47), and Calloway (0.42). The Loring and Grenada had considerably lower undispersed to dispersed ratios indicating that a much greater proportion of their clay-sized sediment was transported as discrete clay particles.

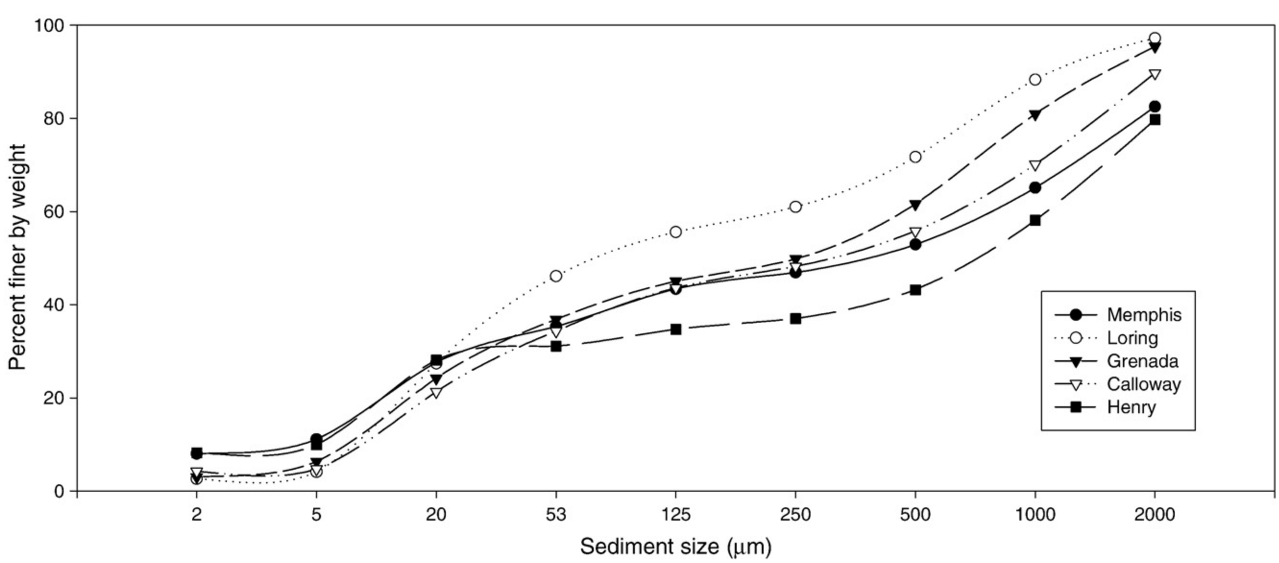

Fig. 1. Cumulative sediment size distribution curves for the five A-horizon soils of the Memphis catena.

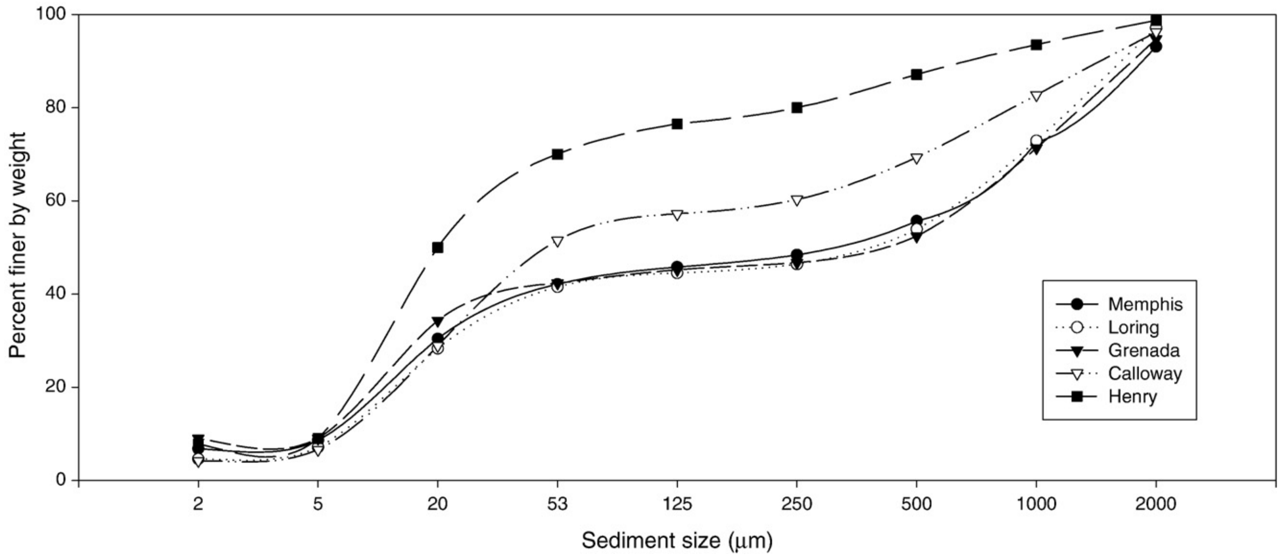

Fig. 2. Cumulative sediment size distribution curves for the five B-horizon soils of the Memphis catena.

In the sand-sized sediment from the B-horizons, the trend corresponded exactly with the soil drainage classes. Specifically, the undispersed to dispersed sediment ratios were 64 for the well-drained Memphis, 59 and 48 for the moderately well-drained Loring and Grenada, 17 for Calloway, and 11 for Henry. Thus, the percentage of sand-sized aggregates in the runoff decreased dramatically as the B-horizon soils became progressively wetter. Generally, the trend is opposite for the silt-sized sediment, with the undispersed to dispersed ratios decreasing from the poorly (Henry) to well-drained (Memphis) soils. The silt fractions in the B-horizons followed this same trend, decreasing in concentration between the lower, wetter slope positions and the higher, better drained sites. Aggregated sediment in the clay size (<2 µm) range from the B-horizons was most concentrated in the Henry soil which had a ratio of 0.64. This was more than twice the undispersed/dispersed ratios for the other soils indicating the presence of a cementing agent at levels exceeding those of the other four soils. Based on the soil chemical data (Table 2), the relatively greater OC contents identified in the Henry B-horizon probably accounts for these differences.

Cumulative sediment size distribution curves of the A- and B-horizons for the five soils are shown in Figs. 1 and 2. Based on the graph for the A-horizon soils (Fig. 1), the Loring soil had a much finer sediment

Table 4
Physical and chemical properties of sediment from Memphis catena soils

Soil/horizon	Size fraction	Total content	Munsell color			RR	MS	Dithionite extractable			Oxalate extractable			Fe_o/	OC
			Hue	Value	Chroma			Fe	Al	Si	Fe	Al	Si	Fe_d	
	µm	g kg^{-1}					$10^{-8}m^3kg^{-1}$	g kg^{-1}							g kg^{-1}
Memphis A	>250	531	8.1 YR	3.0	2.6	1.65	56.7	9.8	1.6	0.8	5.3	1.4	0.3	0.54	25.7
	250–53	117	7.9 YR	2.9	2.4	1.74	62.5	11.9	1.7	0.5	6.0	1.9	0.3	0.50	42.7
	<53	352	8.0 YR	3.1	2.8	1.81	56.0	10.3	3.0	0.1	4.8	3.0	0.2	0.47	21.7
Memphis B	>250	515	7.3 YR	3.3	3.5	2.86	69.8	15.4	2.4	1.0	7.0	2.2	0.5	0.45	5.2
	250–53	63	7.5 YR	3.5	3.7	2.64	64.6	15.6	2.1	0.7	6.9	2.3	0.5	0.44	7.6
	<53	422	7.6 YR	4.1	4.2	2.46	58.3	16.7	4.1	0.6	7.9	4.1	0.3	0.47	4.6
Loring A	>250	390	8.2 YR	3.3	3.0	1.64	68.1	10.3	1.6	0.9	4.8	1.4	0.4	0.47	22.0
	250–53	149	8.3 YR	3.2	2.6	1.38	57.7	9.1	1.3	0.4	4.0	1.5	0.3	0.44	23.0
	<53	461	8.1 YR	3.8	3.2	1.60	56.2	10.4	2.5	0.2	4.0	2.3	0.1	0.38	13.5
Loring B	>250	537	7.4 YR	3.3	3.8	2.99	67.8	15.3	2.4	1.2	7.0	2.2	0.5	0.46	3.8
	250–53	47	7.4 YR	3.5	4.0	2.97	59.7	14.7	2.0	0.8	6.6	2.2	0.5	0.45	5.3
	<53	416	7.5 YR	4.2	4.1	2.44	64.0	16.9	3.9	0.6	7.7	3.9	0.4	0.46	3.4
Grenada A	>250	502	8.3 YR	3.1	3.2	1.75	49.6	13.6	2.0	0.9	4.9	1.6	0.3	0.36	20.3
	250–53	130	8.3 YR	3.1	3.1	1.70	49.2	13.8	1.9	0.5	5.5	1.7	0.4	0.40	19.6
	<53	368	8.6 YR	3.8	3.3	1.22	48.1	13.9	3.6	0.3	4.9	3.2	0.2	0.35	3.5
Grenada B	>250	533	7.9 YR	3.5	4.3	2.58	42.1	17.8	2.9	1.1	5.6	2.3	0.5	0.31	4.4
	250–53	44	8.1 YR	3.8	4.3	2.15	35.6	16.5	2.5	0.7	4.7	2.1	0.5	0.28	5.4
	<53	423	8.1 YR	4.3	4.5	1.99	40.8	19.0	4.2	0.4	5.8	4.0	0.3	0.31	1.4
Calloway A	>250	517	8.5 YR	2.9	2.4	1.24	49.1	11.6	1.9	0.9	7.7	1.7	0.3	0.66	17.7
	250–53	140	8.3 YR	2.8	2.1	1.28	43.5	8.6	1.3	0.6	4.6	1.6	0.3	0.53	33.0
	<53	343	8.3 YR	3.4	2.4	1.20	40.2	6.9	2.7	0.1	3.7	2.9	0.1	0.54	4.4
Calloway B	>250	397	8.6 YR	3.4	3.5	1.44	40.8	15.2	2.4	0.7	4.9	1.5	0.3	0.32	4.8
	250–53	88	8.7 YR	3.7	3.6	1.26	31.8	11.1	1.5	0.4	4.7	1.6	0.4	0.42	5.8
	<53	515	8.7 YR	4.3	3.8	1.15	36.5	11.5	3.0	0.3	5.3	3.1	0.2	0.46	1.7
Henry A	>250	628	8.3 YR	3.4	2.0	1.00	12.8	8.3	2.3	0.8	6.0	2.2	0.2	0.72	29.6
	250–53	60	8.1 YR	3.3	1.9	1.09	18.8	6.3	1.9	0.6	5.7	2.0	0.3	0.90	48.2
	<53	312	8.6 YR	3.8	1.9	0.70	18.1	7.2	1.7	0.7	3.7	2.1	0.3	0.51	21.8
Henry B	>250	199	9.2 YR	3.7	2.1	0.45	18.2	1.8	1.3	0.3	1.9	1.8	0.5	1.06	13.0
	250–53	101	9.4 YR	3.1	1.6	0.31	12.0	0.8	0.8	0.3	1.0	1.5	0.2	1.25	16.1
	<53	700	9.4 YR	3.8	1.6	0.25	4.3	1.2	1.0	0.4	0.5	0.9	0.2	0.42	9.1

size distribution than the others, and is considered more erodible. In terms of the sediment size distribution data, the summation of all size fractions <250 µm gives the following totals for Memphis, Loring, Grenada, Calloway, and Henry: 469; 610; 498; 483; and 372 g kg^{-1}, respectively. Apparently, soil drainage class had no effect on the erodibility of the A horizons, as the more poorly drained soils produced the greater concentrations of the finer sediment size fractions. Apparently, soil wetness was not a factor in the stabilization of soil aggregates from the A-horizon. The sediment size distribution data for the B-horizon soils (Fig. 2) indicate that the soil drainage classes had more influence on aggregation/erodibility. Specifically, the moderately well and well-drained soils (Memphis, Loring, Grenada) are closely grouped, with a generally coarser sediment size distribution. Conversely, the somewhat poorly and poorly drained soils (Calloway, Henry) have a much finer size distribution, especially Henry. The concentrations of sediment <250 µm in the B-horizons is 485, 463, 467, 603, and 801 g kg^{-1} for the Memphis, Loring, Grenada, Calloway, and Henry soils, respectively. This is an indication that the wetter drainage classes have had an effect on the concentrations of cementing agents responsible for the stabilization of these B-horizon aggregates.

Additional physical and chemical properties of the sediment were determined for the >250, 250–53, and the <53 µm fractions (Table 4). The compositing of individual size fractions was necessary since most contained inadequate material for analysis. Based on the data, the distribution of the sediment properties is both size and horizon dependent.

The relative distribution of sediment properties between A- and B-horizon sources was similar to those of source material. The trend with Munsell hue indicates a slight decrease in A-horizon sediment and an increase in the B-horizon as size distributions decrease which corresponds to the increases in soil clay and extractable Fe recorded for the soils (Tables 1 and 2). This is substantiated by the RR values which are inversely related to hue. Magnetic susceptibility decreases with sediment size in both the A- and B-horizons. This is an indication that the magnetic mineral responsible, presumably magnetite, is concentrated in the coarser sand-sized fractions.

The Fe_d contents increased slightly in the finer sediment sizes for the Memphis, Loring, and Grenada soils, but declined in the sediment from the poorly drained Calloway and Henry soils. The Al_d also increased with a decrease in sediment size for all soils except Henry, and Si_d decreased steadily between the coarser and finer sediment sizes. The Fe_o contents were generally greatest in the <53 µm fractions of the sediment from the B-horizon, but the minimum Fe_o contents were associated with the <53 µm fractions of the A-horizon sediment, disregarding the Henry soil. The relationship between Al_o and sediment size fraction was consistent between horizons, reaching a maximum in the <53 µm fraction, again with the exception of the Henry soil where a decrease was recorded. Apparently, these soil/sediment properties are controlled by clay distributions. The Si_o component, which is considered an amorphous phase, decreased consistently with a decrease in sediment size distribution. This suggests that this soil component is involved in the stabilization of the larger aggregates since in most cases the >250 µm fraction is the most concentrated. The Calloway and Henry B-horizons being exceptions. Generally, the Fe_o/Fe_d ratios decreased with sediment size for the A-horizon sources, but in many cases there were no differences observed between the various size fractions in the B-horizons other than a three-fold decrease in the Henry B-horizon. Normally, the higher Fe_o/Fe_d ratios contribute to greater aggregate stability, however, such a relationship is not readily apparent with these data. In all cases, OC is most concentrated in the 250 to 53 µm fractions followed by the >250 and <53 µm fractions. Since the 250 to 53 µm generally contain the least amount of sediment, the contribution of OC to the sediment size distributions measured here is unclear. Such relationships will be addressed in the following section.

Table 5
Correlation coefficients (r^2) determined for sediment size distributions and aggregation (AI) versus several soil properties

Comparison		A-horizon	B-horizon
		r^2	
% sediment >250 µm vs	AI	−0.847*	0.987**
	CEC	0.493	0.966**
	Fe_d	−0.324	0.980**
	Al_d	0.210	0.874*
	Si_d	−0.480	0.957**
	Fe_o	0.866*	0.903*
	Al_o	0.764	0.958**
	Si_o	0.546	0.977**
	Fe_o/Fe_d	0.746	0.311
	OC	0.814*	−0.917**
	Sand	0.711	−0.999**
	Silt	−0.650	−0.961**
	Clay	0.358	0.974**
	RR	−0.697	0.972**
	MS	−0.855*	0.897*
	Hue	0.308	−0.931**
	Value	0.226	0.965**
	Chroma	−0.705	0.897*
% sediment 250–53 µm vs	AI	0.684	−0.937**
	CEC	−0.364	−0.802
	Fe_d	0.484	−0.902*
	Al_d	−0.255	−0.895*
	Si_d	0.228	−0.977**
	Fe_o	−0.757	−0.689
	Al_o	−0.926**	−0.896*
	Si_o	0.779	−0.869*
	Fe_o/Fe_d	−0.789	0.007
	OC	−0.945**	0.741
	Sand	−0.497	0.917**
	Silt	0.893*	0.871*
	Clay	−0.687	0.884*
	RR	0.622	−0.922**
	MS	0.878*	−0.742
	Hue	−0.090	0.890*
	Value	−0.538	0.706
	Chroma	0.769	−0.846*
% sediment <53 µm vs	AI	0.851*	−0.978**
	CEC	−0.516	−0.981**
	Fe_d	0.188	−0.978**
	Al_d	−0.157	−0.853*
	Si_d	0.582	−0.935**
	Fe_o	−0.833*	−0.930**
	Al_o	−0.574	−0.952**
	Si_o	0.336	−0.981**
	Fe_o/Fe_d	−0.636	−0.374
	OC	−0.638	0.937**
	Sand	−0.762	0.998**
	Silt	0.422	0.962**
	Clay	−0.111	−0.975**
	RR	0.663	−0.964**
	MS	0.740	−0.913*
	Hue	−0.406	0.923**
	Value	−0.005	0.946**
	Chroma	0.583	−0.971**
AI vs	CEC	−0.099	0.950**
	Fe_d	0.535	0.985**
	Al_d	0.078	0.919**
	Si_d	0.779	0.982**
	Fe_o	−0.978**	0.847*
	Al_o	−0.683	0.962**
	Si_o	0.133	0.954**
	Fe_o/Fe_d	−0.897*	0.192
	OC	−0.693	−0.857*
	Sand	−0.967**	−0.984**
	Silt	0.428	0.964**
	Clay	0.032	0.974**
	RR	0.954**	0.964**
	MS	0.889*	0.850*
	Hue	−0.647	−0.919**
	Value	−0.388	−0.883*
	Chroma	0.728	0.945**

*,**Indicates significance at the p=0.05 and 0.01 probability levels, respectively.

3.3. Statistical analyses

Correlation coefficients were determined for the various sediment size fractions versus soil properties from the A- and B-horizons (Table 5). The data indicate relatively few statistically significant correlations between sediment size distributions and soil properties for the A-horizon soils. The most consistent, significant correlations between soil properties and sediment size occurred with AI, Fe_o, OC, and MS. The negative correlations for AI versus the >250 μm sediment fraction and the positive correlations with the finer fractions suggest that the A-horizon soils may be eroding primarily as OC stabilized micro-aggregates. In contrast to the A-horizon, practically all the B-horizon soil properties were significantly correlated with all three sediment size ranges. Generally, the highest correlation coefficients were recorded for AI, which was negative for both the 250 to 53, and <53 μm fractions. This negative relationship between the two smaller size fractions and AI is expected because the soils with a higher AI should produce coarser sediment. This is evidenced by the positive correlation between AI and the >250 μm fraction of the B-horizon soils. Likewise, the negative correlations for AI versus the finer sediment fractions are self-explanatory.

When AI was correlated against the other soil properties (Table 5), the Fe_o and sand contents explained most of the AI variability in the A-horizons, followed by Fe_o/Fe_d ratios. These two properties probably account for the high correlation between AI and RR. Soil properties such as magnetic susceptibility and RR have no effect on soil physical properties. Instead, their high correlations with AI are of a secondary nature resulting from a close association with Fe oxides. This may also explain the significant relationship between AI and sand contents in the A-horizon, because the sand fractions in these soils are composed essentially of Fe–Mn nodules. As with the sediment size fractions, AI was highly correlated with most of the B-horizon soil properties. The most highly significant correlations were between AI and extractable Fe, Al, and Si. The sand, silt, and clay fractions were also significantly correlated due to their associations with the oxides.

Regression models were derived (Table 6) using the three sediment size fractions and AI as dependent variables, and the soil properties (Table 5) as the independent variables. In each case, a final model was selected on the basis of increases in R^2. If the increase did not exceed the percentage change in error degrees of freedom between successive models, the independent variable was removed. The percentage of sediment >250 μm in the A-horizon soils was best explained by Fe_o as a single variable, and CEC and MS as the best two variable model which accounted for 97% of the variability. In the B-horizon, sand contents accounted for essentially all of the variation in the >250 μm sediment fraction with an R^2 of 0.999. Organic C was the best single variable model for A-horizon sediment in the 250 to 53 μm range with an R^2 of 0.894. The best two variable model included Si_o and MS. These two soil properties explained 99.7% of the variation in this sediment size range. In the B-horizon, $Si_{d,}$ as the most important single variable model, explained 95% of the variation in the content sediment between 250 and 53 μm. The sediment contents <53 μm from A-horizon soils were best explained by AI as a single variable model, and by Munsell value and MS in a two variable model. Sand contents explained essentially all of the variation in the B-horizon sediment.

The regression models for AI indicated that Fe_o and Fe_d were the most important A- and B-horizon soil properties, respectively, in terms of accounting for its variation. The negative relationship between AI and Fe_o for the A-horizon soils is not fully understood since % sediment >250 μm is positively correlated with Fe_o contents. However, this may indicate a difference in physical form (discrete particles vs coatings) and/or mineralogy of Fe_o soil component between A- and B-horizons as a function of sediment size which would affect its influence on aggregate stabilization.

Table 6
Multiple linear regression models for sediment size distributions and aggregation index (AI) as a function of soil properties

Dependent variable	Horizon	N	Independent variables in model	Regression model	r^2 or R^2
% sediment >250 μm	A	5	1	112.688 + 85.544 Fe_o	0.750
			2	143.146 + 35.719 CEC − 3.498 MS	0.970**
	B	5	1	619.499 − 9.164 Sand	0.999**
% sediment 250–53 μm	A	5	1	221.452 − 4.601 OC	0.894*
			2	− 59.509 + 442.618 Si_o + 1.152 MS	0.997**
	B	5	1	132.157 − 75.483 Si_d	0.954**
% sediment <53 μm	A	5	1	− 20.879 + 6.559 AI	0.724
			2	− 1256.161 + 449.544 value + 3.689 MS	0.999**
	B	5	1	341.155 + 7.702 Sand	0.996**
AI	A	5	1	98.090 − 8.209 Fe_o	0.957**
	B	5	1	39.572 + 1.474 Fe_d	0.970**

*,**Indicates significance at the p = 0.05 and 0.01 probability levels, respectively.

4. Conclusions

The soils that comprise the loess uplands of Mississippi exhibit considerable differences in morphology depending upon where they were formed relative to slope position. This is quite evident in soils of the Memphis catena. From the well-drained Memphis soil to the poorly drained Henry on the lower slope positions, substantial changes occur in both physical and chemical properties as a result of increasingly wetter soil conditions which have a significant impact on soil erodibility. Erodibility for these soils is defined by their aggregation index (AI), which is a function of their water dispersible clay and total clay contents. The data from this study indicate that as the soils become wetter, the AI decreases especially in the B-horizons. This change indicates that the soils become progressively more susceptible to water erosion losses. In association with the decline in AI, the most obvious changes in soil properties that have an impact on aggregation are the general losses of Fe, Al, and Si oxides which serve as aggregate cementing agents. Again, the loss of these cementing agents was most pronounced in the B-horizons where the greatest concentrations of fine sediment (<53 μm) were recorded. Regression models results show that Fe_o was the most important soil property controlling AI in the A-horizons, and that Fe_d was most important in the B-horizons. Since erodibility has been shown to vary between soil drainage classes and mapping units, it necessarily follows that erodibility can be mapped at watershed scales for improved erosion prediction.

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